Evaluation of Radiation Damage to VUV–MPPC for MEG II Liquid Xenon Detector

Rina Onda
On behalf of MEG II collaboration
The University of Tokyo
γ Detector of MEG II Experiment

• MEG II experiment searches $\mu \rightarrow e \gamma$ decay, which is one of charged Lepton Flavor Violation.
• Liquid xenon photon detector (LXe) detects energy, position and timing of $\gamma$.
• Scintillation lights from liquid xenon are detected with PMTs and MPPCs.
PDE Degradation of VUV–MPPC in LXe

- PDE for VUV light of the VUV-MPPCs in LXe was observed under $\mu$ beam. $\rightarrow$ Radiation damage??
- It is known that there is no effect on PDE of other types at the dose level of MEG II.

Estimated Radiation in 2019

<table>
<thead>
<tr>
<th>Irradiation Source</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (Gy)</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>neutron (n/cm$^2$)</td>
<td>$2.7 \times 10^6$</td>
</tr>
<tr>
<td>Photon (/mm$^2$)</td>
<td>$5.6 \times 10^{10}$</td>
</tr>
</tbody>
</table>

- Time
- Accumulated Exposure [hours at MEG II intensity]
- MPPC Response under muon beam
- Normalized Response
- Response to LED light
- Response to VUV light
- Accumulated Exposure [hours at MEG II intensity]
- Exposure to muon beam
- Estimated Radiation in 2019
PDE for VUV Light
(γ/neutron irradiated samples)

Reported in JPS (2019/09/17)

We measured PDE of γ/neutron irradiated samples using scintillation light of LXe from α source.

- γ: Co → Ni + e⁻ + γ @ Takasaki Advanced Radiation Research Institute in Jan. 2015.
- neutron: $^9$Be + d$^+$ → $^{10}$B + n @ Kobe University tandem accelerator in Jan. 2015.

<table>
<thead>
<tr>
<th></th>
<th>Dose of Sample</th>
<th>MEG II Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ (Gy)</td>
<td>$1.4 \times 10^3$, $4.1 \times 10^3$</td>
<td>0.6</td>
</tr>
<tr>
<td>neutron (n/cm²)</td>
<td>$4.8 \times 10^9$ – $2.0 \times 10^{12}$</td>
<td>$1.6 \times 10^8$</td>
</tr>
</tbody>
</table>

PDE degradation was not observed for γ/neutron irradiated samples.

Reported in JPS (2019/09/17)
Possible Cause of PDE Degradation

• The issue of the PDE degradation for the VUV-MPPC was discussed with HPK.
• Similar degradation is known for photodiode: **QE of photodiode is reduced after strong UV light irradiation.**
• **Surface damage at Si-SiO₂ interface** is most suspicious.
  • Ionizing particles such as γ, charged particle and **VUV light can damage it.**
  • The electric field near the interface can be reduced by accumulated holes from the ionization.
  • Wavelength dependence of PDE degradation can be explained.

• **Annealing can be effective** to remove the accumulated charge.
VUV Light Irradiation

- **Light source**
  - For irradiation: xenon lamp
  - For measurement: xenon lamp (with filters) borrowed by Dr. Nakamura (YNU)
    LED ($\lambda \sim 380$ nm)

- **Irradiated photo sensor**
  - VUV-MPPC
  - Standard MPPC (S13350-3050PE)

- **Reference photo sensor**
  - SiPD (S12698-02, Hamamatsu), which is tolerant to UV light
  - VUV-MPPC
  - Standard MPPC (S13350-3050PE)

**Expectation:**
- PDE degradation
- Saturation of PDE degradation
- Dependence of the level of PDE degradation on wavelength

Xenon Flash Lamp: L9455-13 (Hamamatsu)
Setups for Irradiation

- The setups were placed in a thermal chamber and the temperature was kept at 25°C.
- Photo sensors were mounted on a support structure.
- They were irradiated directly with the xenon lamp.
Setups for Measurement

• For the measurements, light from a xenon lamp was reduced with some filters.
  • bandpass filters to select VUV light
    \( \lambda_1 = 193.0 \text{ nm}, T_1 = 26\%, \text{ FWHM}_1 = 20.0 \text{ nm} \)
    \( \lambda_2 = 181.0 \text{ nm}, T_2 = 28.2\%, \text{ FWHM}_2 = 38.5 \text{ nm} \)
  • ND filter to reduce light
    \( T = 3.3\% @ \lambda \sim 190 \text{ nm} \)

• Charge was measured by recording waveforms with an oscilloscope or a waveform digitizer.
Flow of VUV Light Irradiation

The experiment was done in the three steps.

Irradiation
- Stability of Light
- PDE for VUV light
- PDE for visible light

Annealing
- PDE for VUV light
- PDE for visible light
- I-V curve

Reirradiation
- PDE for VUV light
- PDE for visible light
Stability of Light

- Current of irradiate SiPD for a xenon lamp started to decrease though that of non-irradiated SiPD was stable. → QE of the irradiated SiPD decreased.
- Current of irradiate SiPD for LED is increasing though that of non-irradiated SiPD was almost stable. → Effect of UV cleaning? (ref:https://www.ushio.co.jp/jp/technology/glossary/glossary_ha/vuvcleaning.html)
- Current of non-irradiated SiPD for LED slightly decreased in the last 200 hours. → Light yields of LED may have decreased.
PDE for VUV Light

Relative Charge during Irradiation

- Charge of irradiated VUV-MPPCs decreased and was saturated at 35%.
- The degradation was $>10^3$ times slower than that observed by LXe. $\leftarrow$ Lower temperature accelerate it?
- Charge of non-irradiated sample was stable though there was a slight increase. $\leftarrow$ Effect of UV cleaning?
- Charge of irradiated standard MPPCs also was saturated at 70%.
- Charge of a non-irradiated standard MPPC decreased gradually. $\leftarrow$ probably because of light leakage from the irradiation source.
- The irradiated samples seemed to be annealed in room temperature during 12 day intermission. $\Rightarrow$ 11% recovery

Intensity: $5.2 \times 10^{13}$ photons/mm$^2$/h @ $\lambda \approx 190$ nm
Total dose: $3.1 \times 10^{16}$ photons/mm$^2$ @ $\lambda \approx 190$ nm

*markers of similar colors correspond to different chips on the same VUV-MPPC or different standard MPPCs
PDE for NUV Light

- Charge decrease of irradiated samples also observed for visible light.
- Charge of irradiated VUV-MPPCs decreased and was saturated at 25%.
- Charge of irradiated standard MPPCs also decreased and was saturated at 80%.
- The annealing effect was also observed. → 8% recovery
Wavelength Dependence of PDE Degradation

- PDE degradation of VUV-MPPC for NUV light was greater than that for VUV light. Can be explained by **wavelength dependence of absorption**:
  - Absorption depth in Si is the minimum at $\lambda \sim 280$ nm.
  - Other components such as absorption in SiO$_2$ can also affect the dependence.
- Inconsistency b/w VUV-MPPC and standard MPPC can be caused by structure differences.
Annealing

- The irradiated VUV-MPPC was annealed for 45 hours.
- It was exposed to room light with the reverse bias voltage of 70 V.
- Current was ~30 mA and surface temperature reached ~70°C.
- PDE for both light source was recovered completely.
• Dark current of the VUV-MPPC increased by irradiation.
  ➢ Increase of current below the break down voltage was significant. ➣ Increase of surface current
• Annealing reduced it to some extent, but not completely.
• There was no difference in the standard MPPCs.

Difference of structures or the damage level?
Reirradiation after Annealing

- Reirradiation was performed after annealing.
- The speed of PDE degradation seems to become slower than that before annealing.
- It was reduced gradually.
  → supposed to be saturated again.
Summary

• Irradiation using a xenon lamp was performed at room temperature.
• Total dose was $3.1 \times 10^{16}$ photons/mm$^2$ @ $\lambda \sim 190$ nm. (though there was a PDE recovery during intermission)
• PDE degradation was observed.
  • The degradation saturated as expected.
  • The speed is much slower than that observed by LXe.
    $\Rightarrow$ Accelerated by lower temperature? (see 17aG22-8)
• Wavelength dependence was inconsistent to the expectation.
• The dependence was not the same b/w the VUV-MPPC and the standard MPPC.

<table>
<thead>
<tr>
<th>PDE$<em>{after}$ / PDE$</em>{before}$</th>
<th>VUV light</th>
<th>NUV light</th>
</tr>
</thead>
<tbody>
<tr>
<td>VUV-MPPC</td>
<td>35%</td>
<td>25%</td>
</tr>
<tr>
<td>Standard MPPC</td>
<td>70%</td>
<td>80%</td>
</tr>
</tbody>
</table>

• PDE recovered completely thanks to annealing.
Prospects

• Precise estimation of the dose level
  • Irradiation light included all wavelengths from a xenon lamp.
    → It was difficult to estimate the dose level with the current setups.
  • We will use a 20W module (×4 powerful!!).
    → Irradiation can finish in reasonable time (~1 month) even with a bandpass filter.

• Study on wavelength dependence
  • We observed differences of PDE degradation depending on wavelength.

<table>
<thead>
<tr>
<th>PDE_after / PDE_before</th>
<th>VUV light</th>
<th>NUV light</th>
</tr>
</thead>
<tbody>
<tr>
<td>VUV-MPPC</td>
<td>35%</td>
<td>25%</td>
</tr>
<tr>
<td>Standard MPPC</td>
<td>70%</td>
<td>80%</td>
</tr>
</tbody>
</table>

• We can monitor PDE for several wavelengths using LEDs and a xenon lamp:
  • 181 or 193 nm from a xenon lamp
  • 280, 380, 465, 569, 645 nm from LEDs
Backup Slides
• Temperature around the VUV-MPPC was monitored.
• There is an increase at the beginning of each irradiation.
• It was stable within 1°C.
Spec of ND Filters

UVFS Reflective ND Filter, OD = 1.0

Transmission (%) vs. Optical Density vs. Wavelength (nm)

OD = \log_{10}\left(\frac{1}{T}\right)

UVFS Reflective ND Filter, OD = 3.0

Transmission (%) vs. Optical Density vs. Wavelength (nm)

OD = \log_{10}\left(\frac{1}{T}\right)

UVFS Reflective ND Filter, OD = 2.0

Transmission (%) vs. Optical Density vs. Wavelength (nm)

OD = \log_{10}\left(\frac{1}{T}\right)

UVFS Reflective ND Filter, OD = 4.0

Transmission (%) vs. Optical Density vs. Wavelength (nm)

OD = \log_{10}\left(\frac{1}{T}\right)
Spec of Bandpass Filters

193nm Deep UV Bandpass Filter
Theoretical Transmission
FOR REFERENCE ONLY
After the irradiation, color of glue(?) which fixes the quartz window to the VUV-MPPC was changed.
↔ The window peeled off during the previous irradiation.
Gas Annealing

- Irradiated VUV-MPPC was annealed @ 45°C in a thermal chamber.
- Non-irradiated VUV-MPPC was annealed @ 70°C beforehand.
- Temperature dependence is included.
  - The first drops: increase
  - The last jumps: decrease
- PDE of the irradiated sample was completely recovered.

*The first point is normalized to be 0.6 as for the irradiated sample.*
Defects in SiO$_2$

The energy levels introduced in the band-gap of SiO$_2$ due to presence of some defects

- The most commonly observed defect
- Can be generated in SiO$_2$ by the irradiation of X-rays, $\gamma$-rays, electrons, and UV light
- Enable VUV light to generate e-h pairs: 5.75 eV $\sim$ 210 nm

Ref: CCD Image Sensors in Deep-Ultraviolet
Photoelectric Effect on Si

- Typically, a photon with an energy of 1.1 eV to 3.1 eV generates a single e-h pair in the Si.
- More energetic photons with energies greater than 3.1 eV can produce multiple e-h pairs.
- For a photon with an energy greater than 10 eV, the average number of electrons generated is

\[ \eta_i = \frac{E_{ph}(eV)}{E_{e-h}} \]

where, \( E_{e-h} \) is the energy required to generate an e-h pair, which for Si is 3.65eV/electron at room temperature.

Therefore, photons with different energies interact with Si in a slightly different manner.
I–V Curve with Bulk Damage

In the region of unit gain ($V \sim 5 \text{ V}$) the dark current increases by about three orders of magnitude after $\Phi_{eq} = 5 \cdot 10^{14} \text{ cm}^{-2}$, whereas above breakdown voltage the increase is more than six orders of magnitude.

Exemplar current-voltage curves for a KETEK SiPM (15 $\mu$ m pixel size) irradiated with neutrons up to $\Phi_{eq} = 5 \cdot 10^{14} \text{ cm}^{-2}$ and operated at -30 $\text{C}$.

xenon lamp

VUV-MPPC

bandpass filter

light shield

VUV light

ND filter

xenon lamp

VUV-MPPC

xenon lamp